TRANSIENT RESPONSE CHARACTERIZATION OF WAVEFORM RECORDERS

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Funded in part by: Sandia National Laboratories

Test methods for characterizing the transient response of waveform recorders are presented, together with typical test results. The methods, based on the use of a precision, programmable step generator developed at NBS, are suitable for recorders having up to 10 bits of resolution and 100 MHz bandwidth.

Introduction

Waveform recorders are subject to a number of types of errors which can limit their ability to accurately characterize transient signals [1, 2, 3, 4]. Principle among these are dynamic linearity errors, impulse response and settling time limitations, transient thermal errors, and time base jitter. An automated measurement system based on a precision programmable step generator has been developed for characterizing such errors in waveform recorders having up to 10-bits of resolution, and bandwidths on the order of 100 MHz.

The test system is designed to output programmable voltage pulses, with one well-defined transition per period, the beginning and terminating levels of which are designated V_1 and V_2. (The transition from V_2 to V_1 is less well characterized, and is not relied upon for most measurements.) Either single shot or repetitive pulses can be generated, with the repetition rate and duty cycle program-mable over many orders of magnitude. The initial and final levels defining the steps are each programmable within the range of ± 1 V for a 50 Ω termination and within ± 5 V for a high impedance load. Voltage steps within these ranges settle smoothly, with no overshoot, to within 0.1% of full scale range in less than 15 and 19 ns, respectively, for small load capacitance. The corresponding 10-90 percent transition durations are approximately 6 ns and 7 ns. The voltage step waveform has been characterized by independent means, and has been shown to approximate a simple exponential response. At high values of output capacitance, the more slowly rising waveform becomes sufficiently close to an ideal exponential that it can be used for dynamic measurements of linearity errors.

System Description

A block diagram of the complete test system is given in figure 1. Overall control is provided via the IEEE 488 bus, for which an internal listener interface has been provided. The waveform recorder under test is also interfaced to the controller via this bus. To minimize load capacitance, the output circuit of the step generator has been designed as a small hand-sized package which connects directly to the input terminals in the same fashion as many sampling heads for sampling oscilloscopes. The generator's power and control signals are provided by a separate support package via a flexible umbilical cable.

A functional diagram of the output circuit of the step generator is shown in figure 2. A more detailed

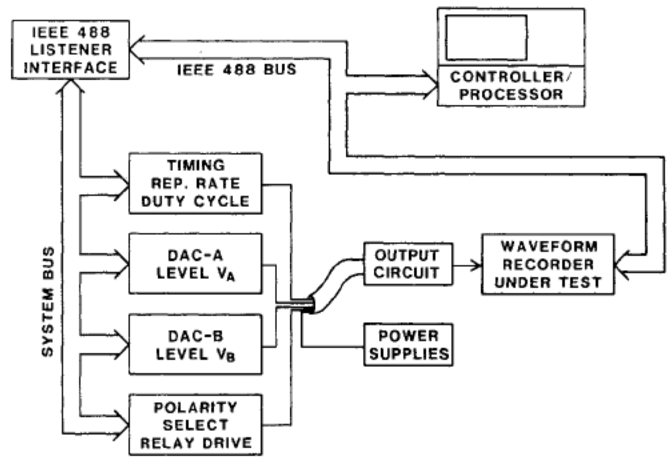

Fig. 1. Block diagram of test system.

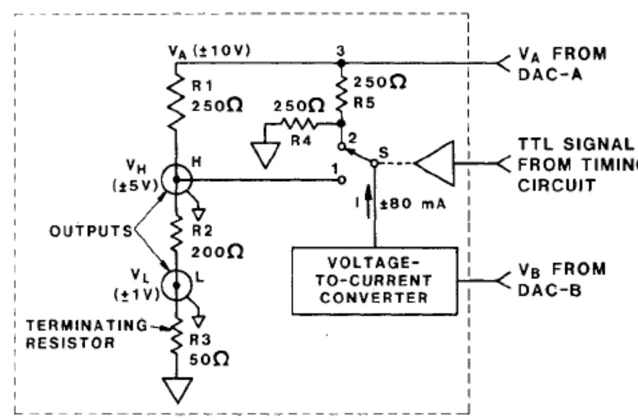

Fig. 2. Simplified diagram of step generator output circuit.

description can be found in reference [5]. Two output ranges are provided: a ±5 V range from output H, intended for high impedance loads, and a ±1 V range from output L for 50 Ω loads. When output L is used, the 50 Ω terminating resistor shown in the figure is actually the input impedance of the test device; otherwise, a 50 Ω coaxial termination is used. The precision step is generated by switching the current source from position 1 to 2. After switching, all active elements are isolated from terminal 1. Consequently, the transition is essentially an exponential waveform determined by the 125 Ω output resistance and the total capacitance between terminal H and ground.

As was previously mentioned, highly accurate exponential waveforms are produced by the generator at higher levels of output capacitance. These waveforms are readily obtained by shunting output terminal H

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1. REPORT DATE **JUN 1985**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE
Transient Response Characterization Of Waveform Recorders

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Electronic Instrumentation and Metrology Electrosystems Division National BureauÂ·of Standards Gaithersburg, MD 20899

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a REPORT **unclassified**	b ABSTRACT **unclassified**	c THIS PAGE **unclassified**	**SAR**	**4**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

with high quality capacitors contained in small in-line enclosures which can be connected directly to the output terminal H.

Dynamic Linearity Testing

Exponential waveforms having transition durations of 0.55 μs or longer are available for dynamic linearity testing using external capacitors. The deviation of these waveforms from the true exponential response has been determined using a sampling voltage tracker [6] to measure the waveforms, and then fitting an ideal model of the form $Y = A_1 - A_2e^{Bt}$ to the data using a nonlinear least-squares curve fitting routine. The errors in these waveforms, as indicated by the residuals of the curve fitting process, are less than 0.05% as shown in Table 1.

TABLE 1

Performance Specifications

Static Errors	V_2	V_1	
Offset	0.01	1.0	% FSR
Gain	0.01	1.0	% FSR
Linearity (Max)	0.02	0.5	% FSR
Noise (40 MHz BW)	<500	<500	μV p-p
Step Limitations	±5 V	± 1 V	
Transition Duration	7	6	ns
Settling Time			
0.1%	19	15	ns
0.02%	26	22	ns
Equivalent Bandwidth	50	58	MHz
Droop/Abberations After Settling	<0.02	<0.02	% FRS
Exponential Waveforms	0.55 μs	27.5 μs	
Deviation From Ideal Waveform (Max)	0.05	0.01	% FSR
rms	0.01	0.006	% FSR
Duty Cycle Dependence			
V_2 Level Change With Duty Cycle (5%-95%)			
0-100 ms		<0.02	% FSR
Max. Final Change (30 s)		<0.05	% FSR

Dynamic linearity measurements are made in the same way by digitizing the exponential waveforms with the recorder under test. Once the waveform has been recorded, the linearity errors are computed from the residuals of the curvefit.

Results of two dynamic linearity tests, one performed on a 10-bit, 60 MHz (sampling rate) recorder and the other on an 8-bit, 200 MHz unit, are presented in figures 3 and 4. The first shows the linearity errors (residuals) of the recorder tested with a waveform having a 27.5 μs transition duration. The maximum and rms errors are 1.5 and 0.42 least significant bits (LSB), respectively. Figure 4 shows the errors with an exponential input having a 0.55 μs transition duration. For this instrument, the maximum and rms errors are 1.3 and 0.46 LSB. In both cases, the ideal maximum and rms error limits are 0.5 and 0.29 LSB, respectively.

Dynamic linearity measurements of this type include errors resulting from ideal quantization uncertainty and time base jitter, as well as differential and integral linearity errors.

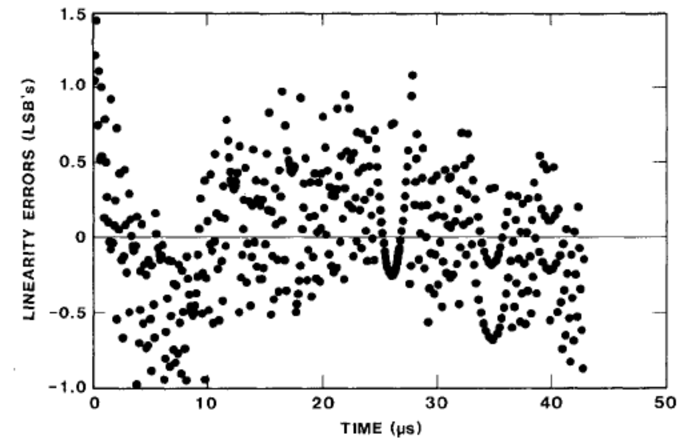

Fig. 3. Dynamic linearity errors of 10-bit, 60 MHz recorder with exponential input signal having 27.5 μs transition duration.

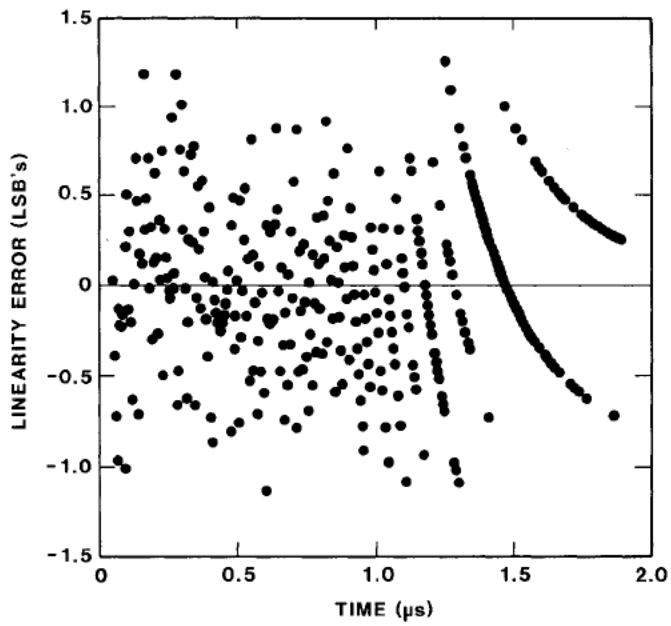

Fig. 4. Dynamic linearity errors of 8-bit, 200 MHz recorder with exponential input signal having 0.55 μs transition duration.

Step Response Measurements

Measurements of step, inpulse, and frequency response, as well as transition duration and settling time can, in principle, all be made directly using the step generator, simply by recording the response to a step, and calculating the desired parameters from the recorded data. In practice, however, two points must be taken into consideration. First, the sampling rate of the test recorder limits the effective bandwidth of the measurement. Because of aliasing errors which result when using a wideband input step, this limitation makes it impossible to characterize the

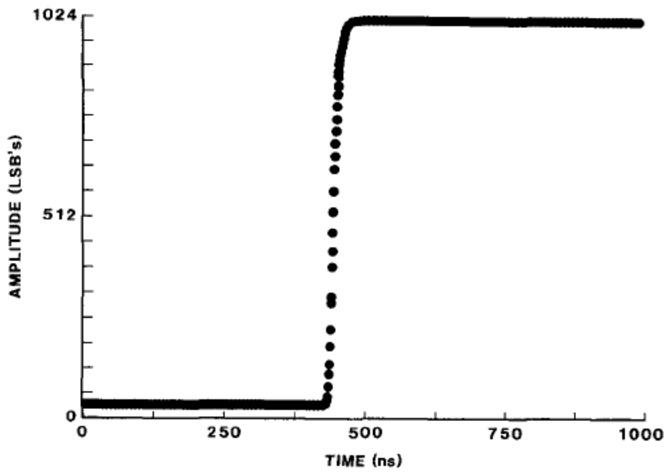

Fig. 5. Step response of 10-bit, 60 MHz recorder, measured using equivalent time method (0.98 ns / sample).

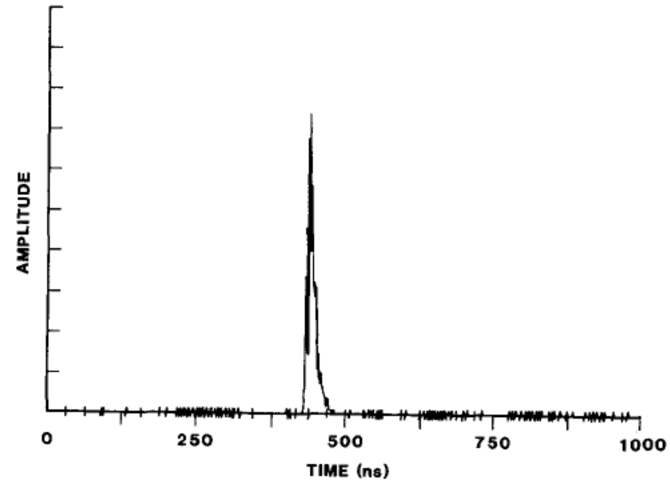

Fig. 6. Impulse response calculated from step response data of figure 5.

frequency response with reasonable accuracy. The second point is that the input step itself has finite equivalent bandwidth (see Table 1), and for very fast recorders, its frequency response may not be flat enough to ignore.

The sampling rate limitation can often be overcome by extracting equivalent time sampling data from a single record, provided that the repetition rate of the input step is selected appropriately, as follows. Set the ratio of the sample rate, f_s, to the step repetition rate f_r, so that $(N-1) < (f_s/f_r) < N$, where N is some integer, thus not allowing f_s and f_r to be phaselocked.

With the step generator, this is accomplished using an external, programmable frequency synthesized source. If, under these conditions, every Nth sample is taken from the record of length M, then the resulting M/N data points will represent equivalent time samples of the original waveform. The exact repetition rate needed to obtain one complete period sampled in equivalent time can be calculated, given a choice of N, from

$$f_r = (f_s / N)(N/M + 1).$$

Note that N/M is the reciprocal of the number of samples that will be in the final record, so that this ratio determines the number of equivalent time samples in one period of the input step. It can be seen from this relationship that the measurement bandwidth is directly proportional to the record length. The interval between the equivalent time samples is given by

$$\Delta t = N(1/f_s - 1/Nf_r).$$

Problems imposed by the limited bandwidth of the step generator can be overcome to some extent, by mathematically deconcolving its response from the recorded response of the waveform recorder under test [7]. The ability to accurately measure the input step using independent, equivalent time techniques makes it possible to at least double the effective bandwidth of measurements made with the step generator. In a future paper, the application and results of deconvolution techniques will be presented.

Some typical test results are given in figures 5-8 for a 10-bit, 60 MHz recorder. These plots give, in order, recorded step response, impulse response, frequency response (showing the computed 3 dB point at

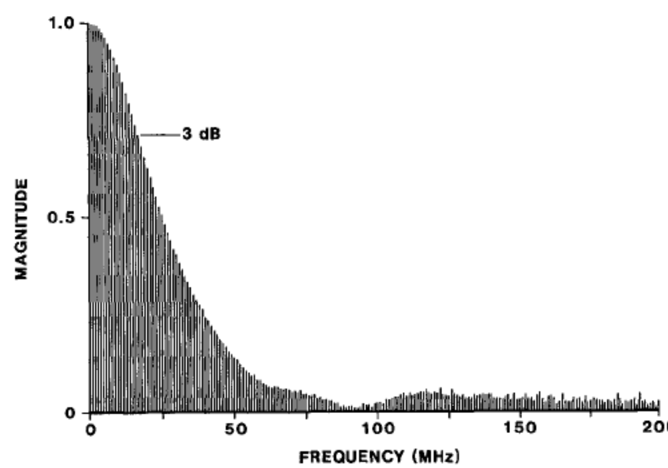

Fig. 7. Frequency response calculated from impulse response data of figure 6. The bandwidth (3 dB point) thus measured is 17 MHz vs. 15 MHz claimed by the manufacturer.

17 MHz), and settling with apparent undershoot of approximately 8 LSBs. Equivalent time sampling was used for all measurements except settling time, with an equivalent sampling interval of 0.98 ns.

To illustrate the utility of such data in predicting the response of a particular waveform recorder when digitizing real-world signals, figure 9 presents an example in which a double exponential waveform is considered. The figure shows an ideal waveform (0.125/10 μs rise/fall time) together with the response error predicted by convolving it with the measured impulse response. Distortion, causing error in the peak value on the order of 7 LSBs, is plotted in figure 9-b. To arrive at an overall estimate of the errors which would likely occur when digitizing such a candidate waveform, the dynamic linearity errors, as presented in figure 3, should also be included.

Testing of Transient Thermal Response

It is common practice to calibrate waveform recorders using static measurement methods. These data are used, if deemed necessary, to correct the actual data obtained when transient waveforms are recorded. In fact, such a process is used in the self calibration

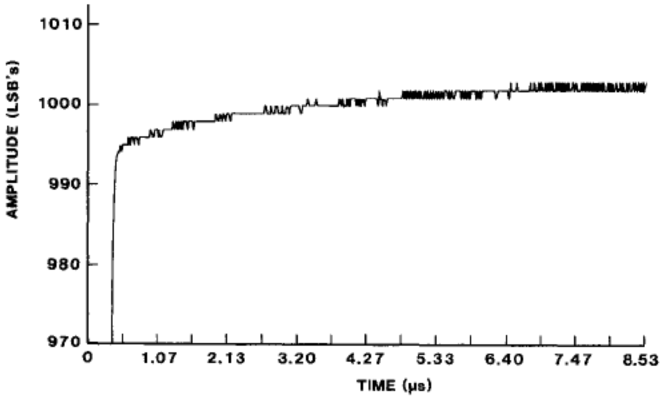

Fig. 8. Expanded view of step response of 10-bit, 60 MHz recorder, showing 8 LSB undershoot and settling time of approximately 6 μs to 1 LSB.

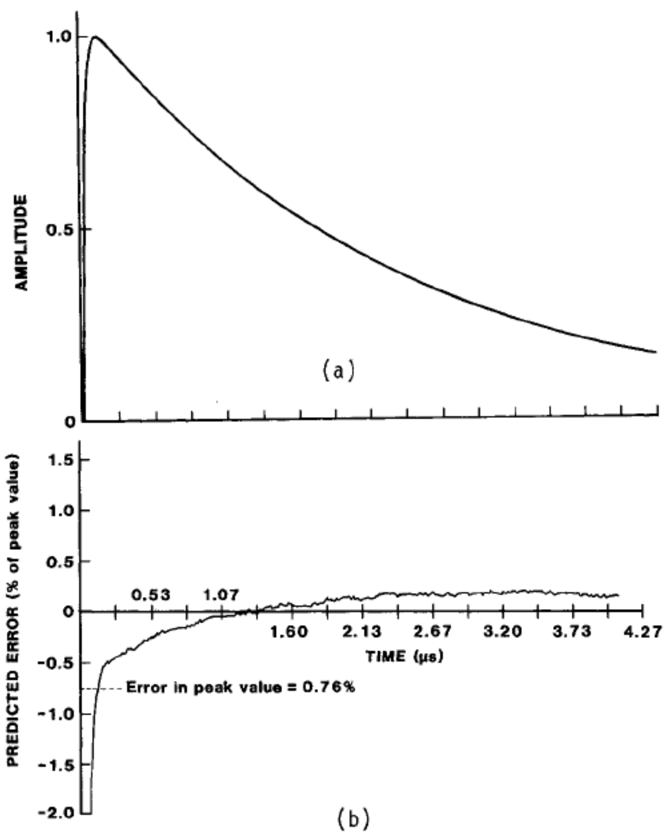

Fig. 9. Ideal double exponential input waveform with 0.125/10 μs rise/fall time (a), and predicted response error (b).

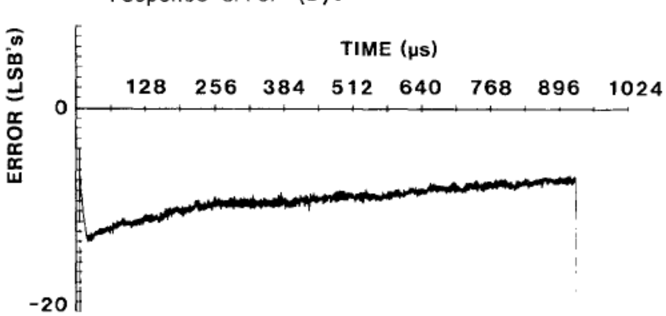

Fig. 10. Transient thermal response of 10-bit, 20 MHz recorder.

routines of several commercial recorders. Unfortunately, even for very slow events, the waveform recorder will likely respond differently to transient signal levels than to dc levels, primarily because of internal transient thermal imbalances which can have rather long time constants. Because these effects are related to signal power, they are nonlinear and thus cannot be represented simply by a transfer function. The magnitude of these effects are easily measured with the step generator however, by first recording one half cycle of a low frequency square wave, and then subtracting from it the record of a dc signal having the same value as the recorded level of the square wave. If transient thermal errors are present, they will appear in the resulting difference between the two records. Figure 10 shows the results of such a test in which a 500 Hz square wave of nearly full scale amplitude has been used. The recording of the upper level of the square wave has been subtracted from a recording of the equivalent dc level. Note the initial overshoot of about 30 μs duration, followed by the long, slowly decaying tail. The peak errors are 12 LSBs.

Conclusions

The step response test system that has been described is capable of accurately measuring many error parameters that are important in assessing the overall transient response of waveform recorders. Fast, accurate settling, together with the programmability of step levels, duty cycles, and repetition rates provides the means needed to measure and separate both linear and nonlinear effects, and to provide information relevant to both the time and frequency domains.

Additional work under way in this area includes the development of a faster generator test head, with a goal of a 2 ns transition duration and settling to 0.1% in 8 ns. This capability would permit the measurement of 10-bit recorders having bandwidths as high as 350 MHz.

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